Fusion

Physics of a Fundamental Energy Source

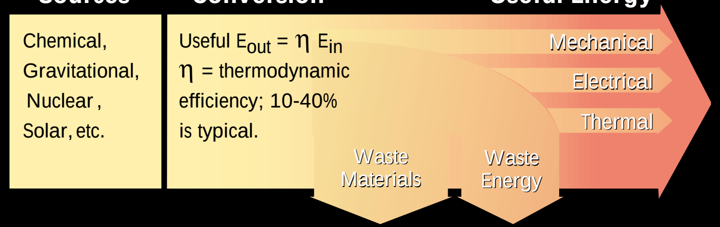
Fusion reactions power the sun and other stars. In fusion reactions, low-mass nuclei combine, or fuse, to form more massive nuclei. The fusion process converts mass (m) into kinetic energy (E), as described by Einstein's formula, $E = mc^2$. In the sun, a sequence of fusion reactions named the p-p chain begins with protons, the nuclei of ordinary hydrogen, and ends with alpha particles, the nuclei of helium atoms. The p-p chain provides most of the sun's energy, and it will continue to do so for billions of years.

To make fusion happen on the earth, atoms must be heated to very high temperatures, typically above 10 million K. In this high-temperature state, the atoms are ionized, forming a plasma. For net energy gain, the plasma must be held together (confined) long enough that many fusion reactions occur. If fusion power plants become practical, they would provide a virtually inexhaustible energy supply because of the abundance of fuels like deuterium. Substantial progress towards this goal has been made.

ENERGY SOURCES & CONVERSIONS

AN OVERVIEW OF ENERGY CONVERSION PROCESSES

Energy can take on many forms, and various processes convert one form into another. While total energy always remains the same, most conversion processes reduce useful energy.



Physical Parameters of Energy-Releasing Reactions

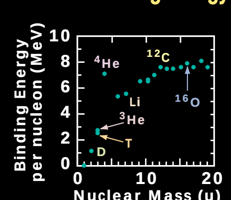
Reaction Type:	Chemical	Fission	Fusion
Sample Reaction	$C + O_2 \Rightarrow CO_2$	$^1n + {}^{235}U \Rightarrow {}^{143}Ba + {}^{91}Kr + 2\,{}^1n$	$D\,(^2H) + T\,(^3H) \Rightarrow {}^4He + {}^1n$
Typical Inputs (to Power Plant)	Coal and Air	UO_2 (3% ^{235}U + 97% ^{238}U)	Deuterium and Lithium
Typical Temp. (K)	1000	1000	100,000,000
Energy Released per kg Fuel (J/kg)	3.3×10^7	2.1×10^{12}	3.4×10^{14}

HOW FUSION REACTIONS WORK

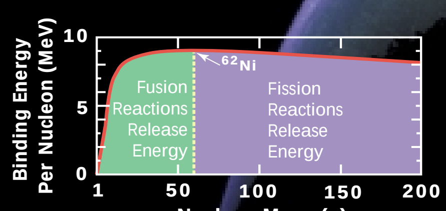
NUCLEAR PHYSICS OF FUSION

Fusion of low-mass elements releases energy, as does fission of high-mass elements.

Binding Energy per Nucleon as a Function of Nuclear Mass



Low-Mass Elements Only



Nuclear Reaction Energy: $\Delta E = k\,(m_i - m_f)\,c^2$

From Einstein's $E = m\,c^2$. ΔE = energy change per reaction; m_i = total initial (reactant) mass; m_f = total final (product) mass. The conversion factor k is 1 in SI units, or 931.466 MeV/uc^2 when E is in MeV and m is in atomic mass units, u.

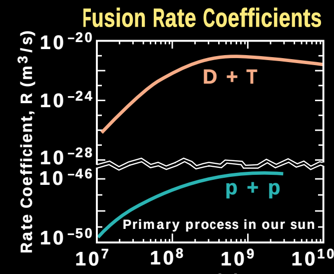
Useful Nuclear Masses

(The electron's mass is 0.000549 u.)

Label	Species	Mass (u*)
n (^{1}n)	neutron	1.008665
p (^{1}H)	proton	1.007276
D (^{2}H)	deuteron	2.013553
T (^{3}H)	triton	3.015500
^{3}He	helium-3	3.014932
α (^{4}He)	helium-4	4.001506

* 1 u = 1.66054×10^{-27} kg = 931.466 MeV/c^2

Fusion Rate Coefficients



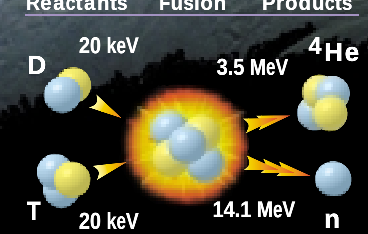
Plasma Fusion Reaction Rate Density = $R\, n_1\, n_2$

n_1, n_2 = densities of reacting species (ions/m^3); R = Rate Coefficient (m^3/s). Multiply by ΔE to get the fusion power density.

TWO IMPORTANT FUSION PROCESSES

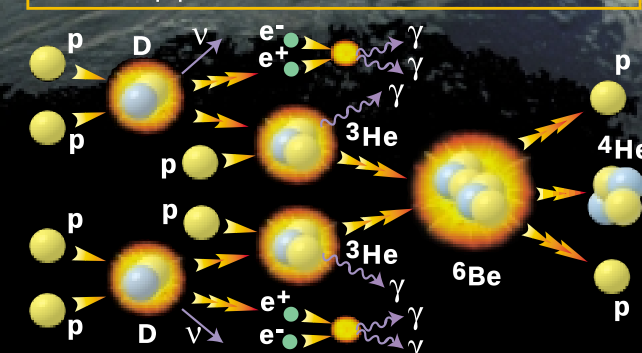
$D + T \Rightarrow {}^4He + {}^1n$

For first generation fusion reactors



1 eV = 1.6022×10^{-19} J. Average particle thermal kinetic energy is 1 eV per 11,600 K.

"p-p": SOLAR FUSION CHAIN



CREATING THE CONDITIONS FOR FUSION

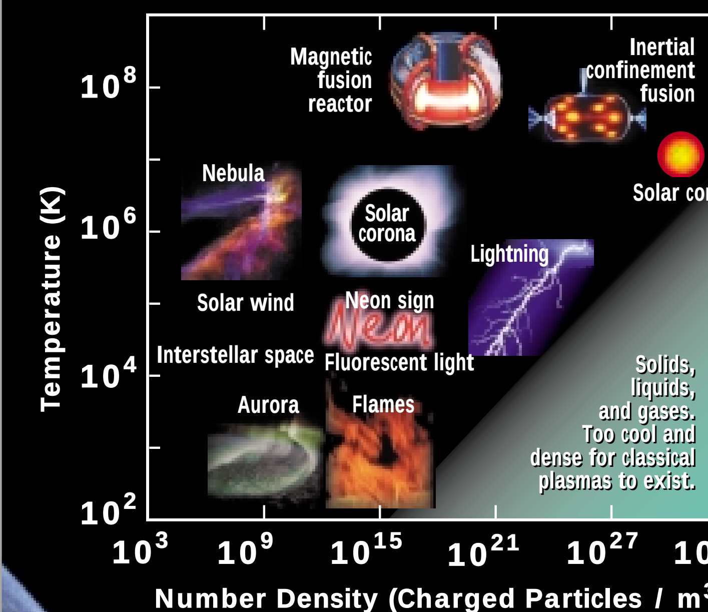
PLASMA CONFINEMENT AND HEATING

Confinement:	Gravity	Magnetic Fields	Inertia
Fusion requires high temperature plasmas confined long enough at high density to release appreciable energy.	Star Formation Plasma 	Tokamak 	Laser Beam-Driven Fusion 
Typical Scales:	<--------- Size: 10^{19} m---------> Plasma Duration: 10^{15} - 10^{18} s	<---------- Size: 10 m ----------> Plasma Duration: 10^{-2} to 10^6 s	<------------ Size: 10^{-1} m ------------> Plasma Duration: 10^{-9} to 10^{-7} s
Heating Mechanisms:	• Compression • Fusion Product Energy	• Electromagnetic Waves • Ohmic Heating (electricity) • Neutral Beam Injection (beams of atomic hydrogen) • Compression • Fusion Product Energy	• Compression (Implosion driven by laser or ion beams, or by x rays from laser or ion beams) • Fusion Product Energy

PLASMAS – THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

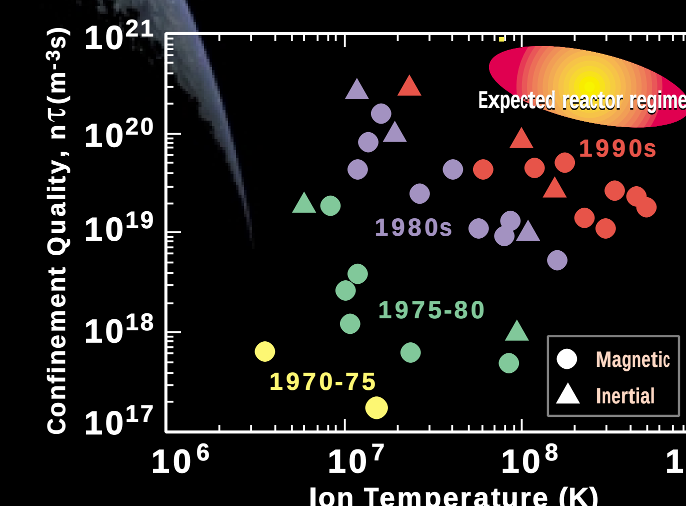
Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.



ACHIEVING FUSION CONDITIONS

EXPERIMENTAL RESULTS IN FUSION RESEARCH

Both inertial and magnetic confinement fusion research have focused on understanding plasma confinement and heating. This research has led to increases in plasma temperature, T, density, n, and energy confinement time, τ. Future power plants based on fusion reactors are expected to produce about 1 GW of power, with plasmas having $n\tau \approx 2 \times 10^{20}$ m^{-3} s and T ≈ 120 million K.



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